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THERMAL STUDIES OF REINFORCED-PLASTIC MATERIALS

Part 2. PROPERTIES OF NINE REINFORCED-PLASTIC LAMINATES

by

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ABSTRACT. The thermal conductivity and specific heat of nine plastic laminates were experimentally evaluated, whereas the thermal diffusivity of the test materials at 140°F was calculated from its relationship to thermal conductivity, specific heat, and density. The data for evaluating the thermal conductivity were obtained by using a guarded hot plate apparatus under steady-state conditions. The values of thermal conductivity were plotted versus temperature, and by the method of least squares an equation was formulated expressing thermal conductivity as a function of temperature. The classical method of mixtures was used to evaluate the specific heat of the test materials at a mean temperature of 140°F.

Along with test results are included recommendations concerning the thermal conductivity apparatus and the specific heat apparatus used in the tests, and a recommendation for the construction of a radiant heat facility for determining thermal diffusivity directly.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

April 1963

U. S. NAVAL ORDNANCE TEST STATION

AN ACTIVITY OF THE BUREAU OF NAVAL WEAPONS

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FOREWORD

The information contained in this report represents the findings of an applied research study of the thermal properties of nine reinforced-plastic laminates at low temperatures. This study was conducted between February 1960 and March 1961 and was supported by Bureau of Naval Weapons Task Assignment RMMP-21-001/216-1/F009-01-016.

Part 1 of this report (Diffusivity of Five Reinforced-Plastic Heat Barriers) presents data on studies performed at the U. S. Naval Ordnance Test Station (NOTS), and Part 2 reports on work performed at the University of New Mexico, under the cognizance of NOTS.

This report was reviewed for technical accuracy by W. K. Smith and R. J. Landry.

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NOMENCLATURE

A	Area, ft^2
C	Specific heat, Btu/(lb)(°F)
C_c	Specific heat of capsule assembly, Btu/(lb)(°F)
C_p	Specific heat at constant pressure, Btu/(lb)(°F)
C_r	Specific heat of standard, taken as 0.0931 Btu/(lb)(°F)
C_s	Specific heat of test specimen, Btu/(lb)(°F)
C_w	Specific heat of calorimetric fluid, Btu/(lb)(°F)
E	Water equivalent of the calorimeter and its accessories, gr
H	Enthalpy (Eq. 26), Btu/lb
H	Constant normal flux (Eq. 14), Btu/(hr)(ft^2)
K	Thermal conductivity, Btu-in/(hr)(ft^2)(°F)
K_m	Arithmetic mean value of thermal conductivity, Btu-in/(hr)(ft^2)(°F)
L	Thickness of slab, in.
M_c	Mass of capsule, gr
M_r	Mass of specific heat standard, gr
M_s	Mass of capsule, gr
M_w	Mass calorimetric fluid, gr
Q	Heat flow, Btu/hr
Q_1	Amount of heat transmitted across face 1, Btu/hr
Q_2	Amount of heat transmitted across face 2, Btu/hr
Q_{gain}	Total heat gain by the parallelepiped, Btu/hr
T	Temperature, °F
T_0	Temperature, at time zero, °F
T_1	Temperature, at position 1, °F
T_2	Temperature, at position 2, °F
$T_{1,2}$	Arithmetic mean temperature, °F
T_c	Temperature of calorimetric fluid before capsule is lowered, extrapolated to time = 10 min, °F
T_h	Temperature of capsule and specimen capsule or standard after heating, °F
T_m	Temperature of mixture, extrapolated to time = 10 min, °F
X,Y,Z	Cartesian coordinates
a,b,c	Constants
p	Subscript refers to constant pressure conditions
r_1,r_2	Inner and outer radii of cylinder, in.
t	Time, hr
x,y,z	Space coordinates, ft
α	Thermal diffusivity, ft^2/hr
ρ	Density, lb/ft^3

INTRODUCTION

To ensure the proper application of newly developed materials, it is necessary to evaluate their physical and chemical properties. In the case of plastic laminates for use as heat-barrier material, thermal diffusivity is an important property. Thermal diffusivity is the parameter that governs the rate of temperature change in a material. Its value depends upon the chemical composition, physical structure, and temperature of the material.

OBJECTIVE

The objective of this investigation was to determine the thermal properties of nine plastic laminates in order to define their thermal capabilities and limitations. The particular thermal properties to be evaluated experimentally were thermal conductivity, K, in the temperature range of 70 to 400°F and specific heat, C, at a mean temperature of 140°F. The thermal diffusivity, α, of the plastics at 140°F was calculated from its relationship to thermal conductivity, specific heat, and density, ρ, which is $\alpha = K/C\rho$.

The insulating materials studied were plastic laminates, which are useful as heat-barrier materials because they have low thermal diffusivities.

APPROACH

Recently, methods (Ref. 1, p. 377, and Ref. 2) have been devised to determine directly the thermal diffusivity of material; however, these methods are still in a state of development. Methods of evaluating thermal diffusivity indirectly by determining thermal conductivity and specific heat under steady-state conditions have been widely accepted and yield reproducible results. An indirect method for evaluating the thermal diffusivity of plastic laminates was employed in this investigation.

Thermal Conductivity. The test apparatus for evaluating the thermal conductivity of plastic laminates was adapted from the guarded hot plate method of the American Society for Testing Materials (A.S.T.M.) (Ref. 3, p. 848). There are three basic types of guarded hot plates: the "Alundum," the "National Research Council," and the "Bureau of Standards." The Alundum guarded hot plate described by A.S.T.M. was developed by the Mellon Institute of Industrial Research. This description was used as a guide throughout the construction of the experimental apparatus for determining thermal conductivity.

A guarded hot plate apparatus consists of a hot and a cold plate opposite and parallel to each other, with the test material inserted between the plates. The hot plate is a metal slab, either circular or square, in which an electric resistance heater is embedded. The cold plate has multiple passages within it so that water can be circulated to maintain as even a temperature as possible. Constant-temperature readings at the hot and cold surfaces of the test material indicate that a condition of steady state has been attained. The total amount of heat transferred is determined by the temperature change and flow rate of the cooling water.

The thermal conductivities of the plastic laminates are calculated from data obtained at thermal equilibrium, using the Fourier equation for one-dimensional heat transfer.

The accuracy of the test measurements depends upon (1) maintenance of steady-state conditions, i.e., constant temperatures, and (2) accurate determinations of measured quantities, such as temperatures, weight of cooling water, dimensions of metering area, and thickness of test samples.

Specific Heat. The A.S.T.M. Tentative Method of Test for Mean Specific Heat of Thermal Insulation (A.S.T.M. Designation C351-59T) (Ref. 4, p. 197) was used to determine the specific heat of the plastic laminates. This method employs the classical method of mixtures, which consists of adding a known mass of material at a known high temperature to a known mass of water at a known low temperature and determining the resulting equilibrium temperature. From this information the specific heat of a material can be determined, provided no chemical reaction takes place.

THEORY

A summary on the theory of heat conduction and a discussion of specific heat closely related to the problem at hand will be given.

HEAT CONDUCTION

The Fourier conduction equation expresses the conditions that govern the transfer of heat through a body. The solution of any particular problem in heat conduction must first of all satisfy this equation. To derive the Fourier equation, consider three Cartesian coordinates X, Y, and Z in any isotropic solid and a small rectangular parallelepiped of dimensions Δx, Δy, and Δz (Ref. 5, p. 12). Let T be the temperature at the center of this parallelepiped. The temperature will be variable throughout the body; however, since the area of the face is so small that the temperature over it is effectively constant, the temperature on any face of the parallelepiped will be greater or less than T by a small amount. Let T_1 and T_2 be the temperatures of the two faces on the $\Delta y\,\Delta z$ plane, where T_1 is the higher temperature. Then the temperatures of the two faces may be written as

$$T_1 = T - (\Delta x/2)(\partial T/\partial x) \text{ and } T_2 = T + (\Delta x/2)(\partial T/\partial x)$$

since the temperature gradient $\partial T/\partial x$ measures the change of temperature per unit length along the X axis, and the distance from the center to the $\Delta y\Delta z$ planes is $\Delta x/2$. The temperature gradient is taken in the direction of heat flow and is negative.

The amount of heat transferred per unit time, Q, across a face may be written as $Q = -KA(\partial T/\partial x)$ where K is the thermal conductivity of the substance and A is the area of the face. Thus,

$$Q_1 = -K\Delta y\Delta z(\partial/\partial x)\left[T - \frac{\Delta x(\partial T/\partial x)}{2}\right]$$

and

$$Q_2 = -K\Delta y\Delta z(\partial/\partial x)\left[T - \frac{\Delta x(\partial T/\partial x)}{2}\right]$$

where Q_1 and Q_2 are the amount of heat transmitted across faces 1 and 2, respectively. The difference between these two quantities is the heat gain caused by the heat flow in the x direction and is equal to

$$Q_{gain} = Q_1 - Q_2 = K(\partial^2 T/\partial x^2)\Delta x\Delta y\Delta z$$

Similar expressions hold for the y and z directions of heat flow. The total heat gain from all directions is equal to

$$Q_{gain} = K(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2)\Delta x \Delta y \Delta z \tag{1}$$

The total amount of heat gain by the parallelepiped per unit time may also be expressed as

$$Q_{gain} = C\rho \Delta x \Delta y \Delta z(\partial T/\partial t) \tag{2}$$

where C and ρ are the specific heat and density, respectively. Therefore, equating Eq. 1 and 2 we obtain

$$C\rho(\partial T/\partial t) = K(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2) \tag{3}$$

or, since $\alpha = K/C\rho$,

$$\partial T/\partial t = \alpha(\partial^2 T/\partial x^2 + \partial^2 T/\partial y^2 + \partial^2 T/\partial z^2) \tag{4}$$

This expression is known as Fourier's conduction equation. The constant α is called the thermal diffusivity of the substance.

The solution of all heat conduction problems involves the evaluation of the temperature as a function of the time and the space coordinates, which satisfies Eq. 3 and 4. The temperature is assumed to be finite and a continuous function satisfying not only the general differential equation, but also certain boundary conditions that are characteristic of each particular problem. Several boundary conditions usually arise in problems of heat conduction (Ref. 6, p. 18):

1. The temperature on the boundary may be constant, or a function of time, or position, or both.
2. The boundary may be impervious to heat.
3. The boundary may have a prescribed heat flux.
4. The heat flux across the boundary may be proportional to the temperature difference between the surface and the surroundings.
5. The heat flux across the boundary may be a nonlinear function of the temperature difference between the surface and the surroundings.
6. Another boundary condition arises when a solid is in contact with a well-stirred fluid or perfect conductor.
7. The boundary may consist of a surface formed by two substances of different thermal conductivity in contact with each other.
8. The boundary may be a surface formed by a solid in contact with the thin skin of a much better conductor.

The experimental method of measuring thermal diffusivity directly is based on the solution of the following problem. Consider an infinite slab of thickness, L, irradiated with a constant normal source of radiant energy, H, on one face ($x = L$). The origin of x is at the unirradiated face of the slab. The general differential equation is

$$\alpha(\partial^2 T/\partial x^2) = \partial T/\partial t$$

With the following boundary conditions:

$$T = T_0 \text{ at } t = 0, \qquad 0 \le x \le L$$

$$T > 0, \qquad \partial T/\partial x = 0 \text{ at } x = 0$$

and

$$H = K(\partial T/\partial x) \text{ at } x = L$$

the solution (Ref. 6, p. 112) is

$$T = T_0 + (HL/K)\left\{\frac{at}{L^2} + \frac{3x^2 - L^2}{6L^2} - \frac{2}{\pi^2}\sum_{n=1}^{\infty}\frac{(-1)^n}{n^2}\exp\left[-\left(\frac{n\pi}{L}\right)^2 at\right]\cos\frac{n\pi x}{L}\right\}$$

For $t > 0.54L^2/a$ the solution reduces to

$$T = T + (H/K)\left(\frac{at}{L} + \frac{3x^2 - L^2}{6L}\right) \tag{5}$$

which shows that the temperature is a linear function of time. From a plot of temperature versus time, the thermal diffusivity of a substance may be determined.

Most methods of measuring thermal conductivity employ the steady state, which occurs when the temperatures of the various points within a system do not change with time. For the steady state, the general equation of conduction reduces to

$$\partial^2T/\partial x^2 + \partial^2T/\partial y^2 + \partial^2T/\partial z^2 = 0$$

If the flow of heat is restricted to one dimension, the equation further reduces to

$$d^2T/dx^2 = 0$$

Letting $P = dT/dx$, then $dP/dx = 0$ and

$$dT/dx = b$$

integrating yields $T = bx + c$. Therefore, at steady state the temperature through the slab is a linear function of x. The heat flux, Q/A, entering and leaving the slab is constant and may be expressed as

$$Q/A = -K(dT/dx)$$

Separating variables, the equation is transformed to

$$(Q/A)dx = -KdT$$

On integrating, and assuming T_1 is the temperature at $x = 0$, then

$$Q\int_0^L dx/A = \int_{T_2}^{T_1} KdT \tag{6}$$

Generally, the variation of thermal conductivity with temperature may be taken as linear, especially if the temperature interval is limited. Assuming that the area does not vary with length and remembering that Q is constant, Eq. 6 yields

$$Q/A = K_m(T_1 - T_2)/L \tag{7}$$

where K_m is the arithmetic mean value of the thermal conductivity over temperature interval T_1 to T_2.

Heat is a manifestation of molecular motion, and the conduction of heat is the transmission of energy from one molecule to another. Different mechanisms of heat conduction are responsible for the widely varying values of thermal conductivity of materials. The principal mechanisms of heat conduction in solids are (1) lattice vibration, (2) motion of free electrons, (3) intermolecular vibration, and (4) radiation within the solid (Ref. 5, p. 9; Ref. 7, p. 7; Ref. 8, p. 190).

The heat-transfer mechanisms in metals are lattice vibration and the motion of free electrons, the latter being the predominant mechanism. Since heat conduction in metals is associated with the presence of free electrons, univalent elements (alkali metals, copper, silver, and gold)

of the periodic system are the best thermal conductors. In general, the two mechanisms, lattice vibration and the motion of free electrons, interact with each other. The net change in thermal conductivity of a metal with temperature is the resultant of the variation of these two mechanisms. An increase in the temperature of most metals will result in a decrease in thermal conductivity. Austin (Ref. 7, p. 45) has reported on the factors that influence the thermal conductivity of metals.

In nonmetallic crystals the heat conduction mechanism is lattice vibration. Theoretically, the thermal conductivity of nonmetallic crystals should vary proportionally to the cube of the absolute temperature up to a maximum value, and then vary inversely as the absolute temperature (Ref. 9, p. 45). The temperature corresponding to the maximum value of thermal conductivity varies with the crystalline material. The maximum thermal conductivity of graphite occurs at approximately −95°F, after which it decreases with temperature (Ref. 10, p. 5B.01.03).

Wilkes (Ref. 11, p. 72) has reported on the factors that affect the value of thermal conductivity of heat insulators. He reports that, in general, (1) the value of thermal conductivity for most insulators increases with increasing temperatures, (2) the thermal conductivity of insulators increases with an increase in density, (3) the direction of heat flow through most heat insulators has little effect on the thermal conductivity, (4) the thermal conductivity of an insulator increases as the moisture content of the insulator increases, (5) the effect of increasing air pressure is to increase the value of the thermal conductivity of insulators, and (6) the thermal conductivity value is not influenced by the rate of heat flow.

SPECIFIC HEAT OF SOLIDS

The specific heat capacity of a body is the amount of heat required to increase the temperature of a unit weight of a body by 1 degree.

The thermodynamic definition of heat capacity at constant pressure is $C_p = (\partial H/\partial T)_p$ where H is enthalpy.

REVIEW OF THE LITERATURE

A brief outline of the techniques and principles of the major methods of determining thermal conductivity and specific heat is given along with references to the literature for more specific details.

METHODS OF MEASURING THERMAL CONDUCTIVITY

The major methods (Ref. 12) of measuring thermal conductivity are the following: (1) Fitch, (2) longitudinal heat flow, (3) Forbes bar, (4) radial heat flow, (5) parallel plate, (6) comparative, (7) electrical, and (8) dynamic or pulse.

The Fitch method (Ref. 13) consists of measuring thermal conductivity by maintaining one surface of the test material at a given temperature, then measuring the temperature gradient in the test material after a steady state of heat transfer is attained. The Fitch apparatus is unique in that a copper slab is used as a calorimeter. This apparatus is particularly suited for materials of low thermal conductivity.

The commonly used longitudinal heat flow method uses a cylindrical bar of test material insulated lengthwise to prevent radial heat losses (Ref. 8, p. 165). A constant temperature source is placed at one end of the bar and a heat sink at the other end. At steady state the temperature gradient in the bar and the quantity of heat transferred through the bar are measured. This apparatus is quite versatile for testing materials varying from insulators to liquid metals.

A modification of the longitudinal heat flow method is known as the Forbes bar method (Ref. 14). This method employs a bath of molten lead at one end of the bar and still air at the other. A knowledge of the density and specific heat of the bar is required. However, recent improvements do not require this information (Ref. 15).

The radial heat flow method uses a hollow cylinder of the test material with a heater inserted in the center (Ref. 16). Suitable guard heaters are provided at the ends. The thermal conductivity of the test specimen is found from the relationship

$$K = Q \ln (r_2/r_1)/2(T_1 - T_2)$$

where r_1 and r_2 are, respectively, inner and outer radii of the test cylinder.

A.S.T.M. (Ref. 3, p. 848) prescribes a parallel plate method for measuring thermal conductivity at steady state. The measurement of thermal conductivity of insulating materials by the guarded hot plate is described in the literature (Ref. 17 and 18). A rapid guarded hot plate method that will apparently yield accurate determinations in 10 to 15 minutes has been reported (Ref. 19).

The early researchers determining thermal conductivity obtained values that were relative rather than absolute. Of note is the modern experimental apparatus by Horak and Krupka (Ref. 20) for making comparative measurements. If one has a material with known thermal conductivity, then the value of thermal conductivity for another material may be found. In this method two bars, a standard and a material of unknown conductivity, are placed in series to ensure equal heat flux through both bars. The thermal conductivity involves the measurement of the temperature gradient in each of the bars and is found by the relationship

$$K_1(dT_2/dx_1) = K_2(dT_2/dx_2)$$

In the electrical method for determining conductivity, a rod is heated by passing an electric current through it while the ends of the rod are kept at ambient temperature. This method gives the ratio of thermal and electrical conductivities. Electrical conductivity may be determined independently of thermal conductivity, which can then be easily calculated.

The pulse method for determination of thermal conductivity was developed by H. J. Angstrom (Ref. 21, 22, and 23) and is actually a measure of the thermal diffusivity. Therefore, in order to determine the thermal conductivity it is necessary to have an accurate knowledge of specific heat and density. The apparatus used in this method consists of a long test bar with an electric heater at one end, whereas the other end extends into still air or into an insulating medium. A steady-state temperature gradient is imposed on the specimen, and a thermal pulse varying sinusoidally with time is superimposed on the hotter end. This temperature disturbance is propagated along the bar at a rate that varies with the thermal diffusivity.

METHODS OF MEASURING SPECIFIC HEAT

The literature described several basically different methods of measuring specific heat: (1) the method of mixtures, (2) the Bunsen method, and (3) other special methods.

The method of mixtures consists of immersing a test specimen at constant temperature into a calorimetric fluid and recording the temperature rise of the adiabatic calorimeter (Ref. 24 and 25). This method has been employed for determining specific heats for the temperature range of 32 to 1300°F. There are many variations of the basic method of using adiabatic calorimeters.

The Bunsen method uses the heat from the test specimen to melt ice that is in thermal equilibrium with water in a closed system (Ref. 26 and 27). This method is described in detail by Seibel and Mason (Ref. 28, p. 29).

Other methods of determining specific heat are Sykes' and Jones' (Ref. 29) and Smith's (Ref. 30). In most determinations, copper is used as a standard for calibration purposes, because of its well known specific heat properties (Ref. 31).

TEST MATERIALS

Three panels of each of the nine plastic laminates studied were prepared for testing at the U. S. Naval Ordnance Test Station. The panels were 7 inches square and 0.25 inch or less in thickness. The test specimens were pressed at 100 lb/in^2 at 350°F for 1 hour, removed from the press, and post-cured for 16 hours at 350°F. The composition of each test specimen is shown below:

Sample	Composition
1	6 sheets of graphite mat impregnated with 101 phenolic resin
2	13 sheets of WC-001 graphite cloth impregnated with 101 phenolic resin
3	7 sheets of 184 Volan (glass cloth with a Volan finish) impregnated with 37-9X phenyl silane resin
4	Thermo-Insulating Compound (TIC-311S) used as received
5	184 Volan impregnated with 37-9X phenyl silane resin
6	Asbestos cloth with one sheet of silver foil in center impregnated with 91LD phenolic resin
7	Asbestos cloth with one sheet of aluminum foil in center impregnated with 91LD phenolic resin
8	Refrasil cloth impregnated with 91LD phenolic resin
9	Similar to samples 3 and 5 plus one coat of plastic primer and two coats of SAF paint (alkyd resin base)
10	Similar to samples 3 and 5 plus one coat of plastic primer and two coats of TIC paint (water base)

Samples 3 and 5 are similar in composition, but they were prepared at different times with slightly different molding and curing cycles, which accounts for the difference in their thermal properties.

TIC-311S, TIC paint, and SAF paint were supplied by the Alim Corporation, 11 Park Place, New York 7, N. Y. The other plastics and resins were supplied by the U. S. Polymeric Chemical Company, Inc., Canal and Ludlow Streets, Stamford, Conn.

The test specimens were prepared for the specific heat determinations by cutting 1.125-inch-diameter disks from the panels for insertion into the capsule assembly described later in this report. The test materials are shown in Fig. 1.

Many laminated reflective foils are especially effective at low and high temperatures, where the low absorptivity and low conductivity of the gap between foils pose a high thermal resistance. Metal foils have found extensive application in the field of cryogenics. Foils of copper, titanium, stainless steel, brass, nickel, tantalum, zirconium, silver, gold, and palladium are readily available in thicknesses of 0.0005 inch and can be made as thin as 0.00005 inch. The application of reflective insulation is relatively new, and the heat transfer theory connected with it is much more complex than that for the usual insulation material. A good discussion of principles governing the use of reflective foils is presented by Wilkes (Ref. 11, p. 109).

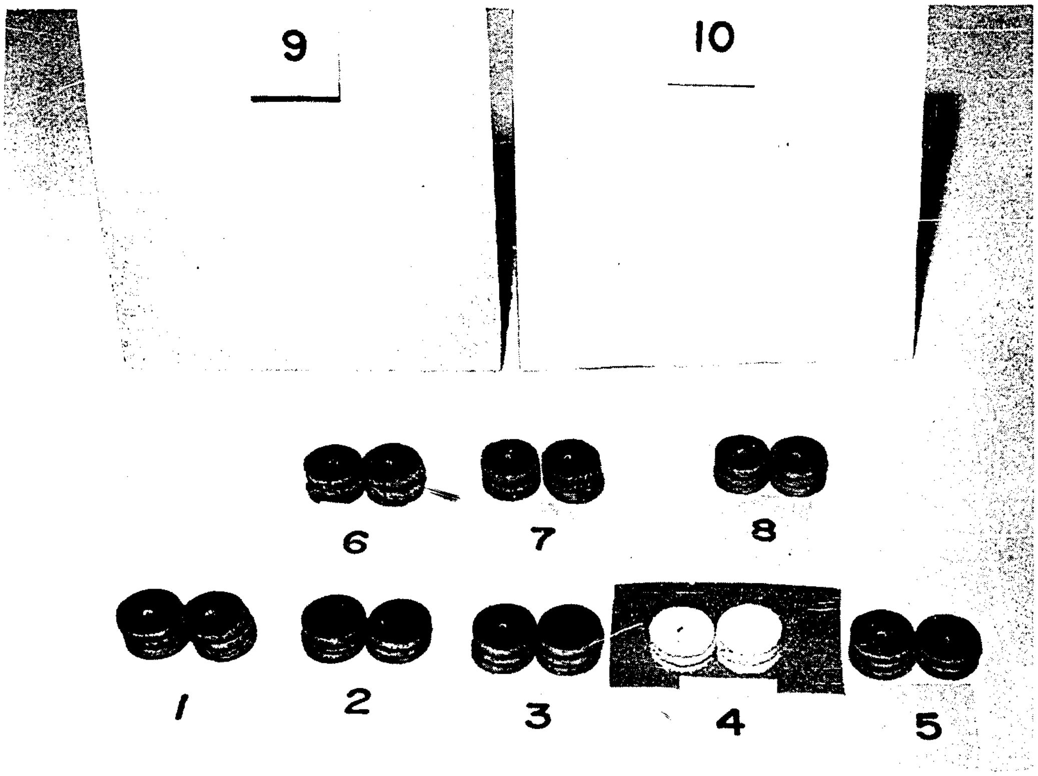

FIG. 1. Test Materials Used in the Thermal Conductivity and Specific Heat Tests.

TIC-311S is a new insulating material, which is applied by spraying or troweling (Ref. 32). Under exposures to temperatures of 300°F and higher, TIC-311S intumesces into a thick, dense foam or spongelike mat 25 to 45 times its original film thickness. The insulating properties of TIC-311S are better than those of fiberglass, especially at temperatures above 1300°F, at which fiberglass melts. Its main disadvantage is that it is water soluble, as is the TIC paint used in sample 10. For this reason SAF paint was formulated from TIC with an alkyd resin base.

EXPERIMENTAL TECHNIQUE

The experimental apparatus for determining the thermal conductivities of the test materials was adapted from the A.S.T.M. Standard Method of Test for Thermal Conductivity by Means of the Guarded Hot Plate (Ref. 3, p. 848). The specific heat apparatus and method were the A.S.T.M. Tentative Method of Test for Mean Specific Heat of Thermal Insulation (Ref. 4, p. 197).

THERMAL CONDUCTIVITY EXPERIMENT

Apparatus. A guarded hot plate apparatus was used to determine the thermal conductivity of the plastic laminates. This apparatus consists of a hot and cold plate in parallel, with the test material inserted between them. A 7-inch-square hot plate was constructed from a 3/4-inch steel slab in which a 7-inch-diameter ceramic-incased electric heater was embedded. The heater required a 115-volt alternating current source and was regulated by a variable transformer. A 1/8-inch-thick asbestos board was cut and laminated to completely incase the hot plate, with the exception of the heating surface. The hot plate surrounded by asbestos sheets and asbestos wool in the instrument box is shown in Fig. 2 together with thermocouples and wire connections to the electric heater.

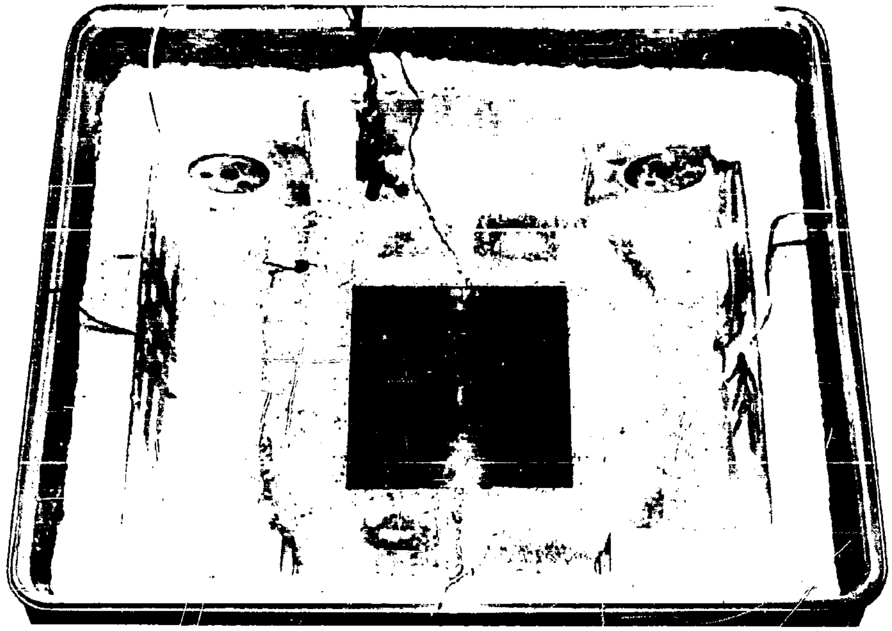

FIG. 2. Hot Plate Assembly.

The cold plate was a 3/4-inch aluminum slab with 1/4-inch holes bored parallel to the cooling surface, permitting the passage of cooling water as shown in Fig. 3. Twelve brass fittings were connected by copper tubing in such a manner as to maintain as even a surface temperature as possible.

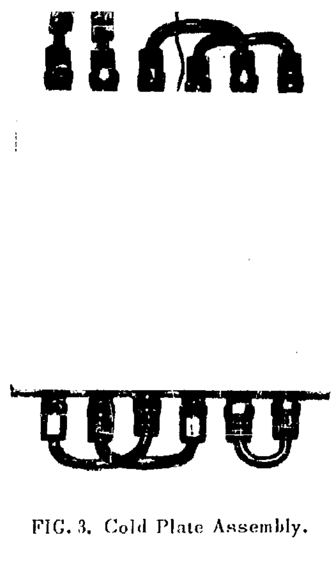

FIG. 3. Cold Plate Assembly.

The inner surfaces of the hot and cold plates had embedded iron-constantan thermocouples for temperature determinations, as did the inlet and outlet water passages of the cold plate. The electromotive force of the thermocouples was measured with a Leeds and Northrup potentiometer. The flow of cooling water to the cold plate was maintained by the use of a constant-head tank. The cooling water flowed from the cold plate into a weighing device in order to measure the rate of flow.

The over-all guarded hot plate apparatus is presented in Fig. 4.

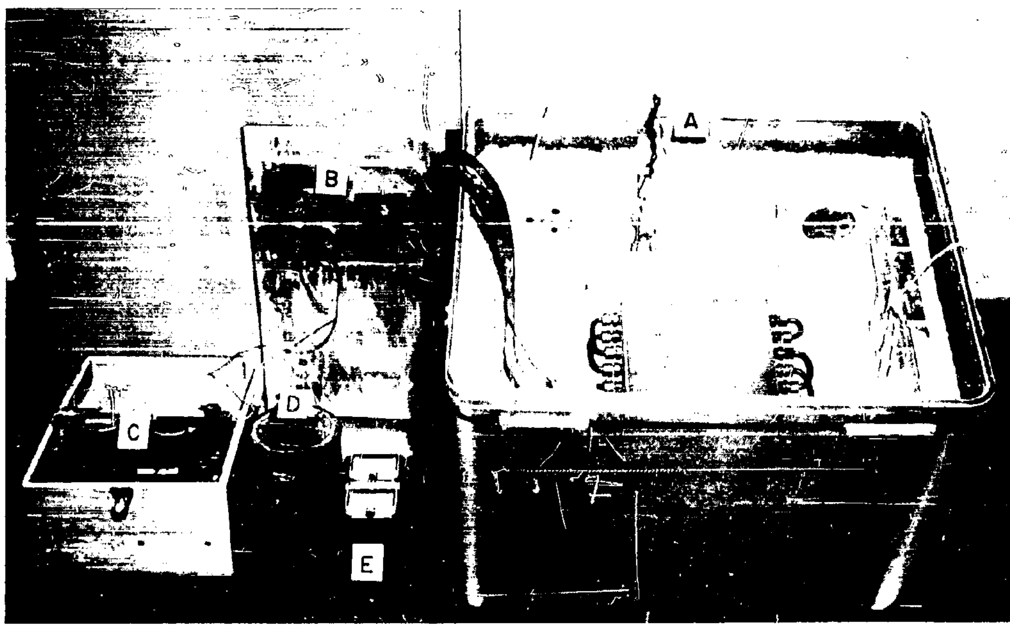

FIG. 4. Guarded Hot Plate Apparatus. (a) Hot and cold plate assembly, (b) thermocouple selector switch, (c) L & N potentiometer, (d) Variac, (e) guard heater wattmeter.

Procedure. The test samples were dried at approximately 215°F to vaporize any excess moisture and weighed after drying, to the nearest 0.01 gram. The volume of the test samples was obtained by measuring the length and width with a scale and the thickness with a Starrett micrometer at a minimum of five locations. From this information the density of each sample was calculated.

After preparation, the specimen was inserted between the hot and cold plates and the entire guarded hot plate apparatus covered with asbestos wool. The variable transformers were set at a predetermined value, and the flow rate of the cooling water was adjusted to give a temperature increase of at least 30°F.

The condition of steady state at any point in the apparatus was reached in approximately 5 hours. At this time the cooling water allowed to flow into the weighing device and collected over a known period of time. Temperature readings of the inner surfaces of the hot and cold plates and of the incoming and outgoing cooling water were recorded. The total amount of heat transferred was determined from the temperature change of the cooling water and the rate of flow.

The thermal conductivity determinations required approximately 6 to 7 hours; some additional time was required to replace test materials for testing. Approximately 2 weeks were required to obtain the thermal conductivity data for each test material.

The thermal conductivity of the plastic laminates was calculated at steady state using the Fourier equation for one-dimensional heat transfer (Eq. 7). The variation of thermal conductivity with temperature over a small temperature interval is usually assumed to be linear and may be represented by the expression $K = a + bT$ where a and b are constants for a given material and T is the temperature in °F. The units of thermal conductivity can be expressed as Btu-in/(hr) (ft^2) (°F). The values of thermal conductivity were plotted versus temperature for each test material, and by the method of least squares an equation was obtained relating thermal conductivity to temperature.

SPECIFIC HEAT EXPERIMENT

Apparatus. The specific heat calorimeter was an unlagged Dewar flask of 665-ml capacity with a 2.75-inch inside diameter and with a variable-speed magnetic stirrer. A differential thermometer with a temperature range of 18 to 28°C, graduated every 0.01°C, was used to determine the temperature rise of the calorimetric fluid (distilled water) during the test. A magnifier was used to facilitate reading the thermometer.

The electric heater used to heat the test specimens consisted of a 10-inch length of brass pipe, of 1.5-inch inside diameter, covered with asbestos paper. The pipe was wound with 85 turns of 22-gage Nichrome wire and insulated completely with a 2-inch-thick pipe insulation. Two composition covers prevented heat loss from the open ends of the heater.

A commercial, copper, electrical bus bar was used as the specific heat standard to determine the water equivalent of the calorimeter. The mean specific heat of copper for the temperature range between 20 and 100°C is 0.0931 Btu/(lb) (°F) (Ref. 4, p. 197).

The test capsule for containing the test specimens consisted of a hollow copper cylinder approximately 1 inch in diameter and 2 inches long. It had a removable cap and a thermocouple well.

The over-all specific heat calorimeter apparatus is shown in Fig. 5. Figure 6 shows the capsule assembly and the necessary accessories.

Procedure. A test specimen was dried. Its weight was determined by first weighing the empty capsule assembly, then the capsule assembly containing the specimen, and then calculating the difference. The capsule containing the specimen was suspended in the heater. Both were heated to a temperature between 203 and 212°F. A period of 4 hours was usually required to reach thermal equilibrium. Distilled water was poured into the Dewar flask. The magnetic stirrer was set at a moderate stirring rate, and this rate was kept constant for all the determinations. After about 10 minutes, to allow for thermal adjustment between the calorimeter and the surroundings, the temperature of the calorimeter (to the nearest 0.001°C) was taken at the end of each 1-minute interval for a period of 9 minutes. At the end of the tenth minute, the capsule was rapidly lowered into the calorimeter and the calorimeter cover quickly replaced. The temperature readings were resumed at the eleventh minute and continued until the slope of the temperature-versus-time curve was constant. The required time for individual runs was 5 to 6 hours, and approximately 2 days for the entire evaluation of a test material.

The following equations, which determine the water equivalent of the calorimeter, the heat capacity of the capsule, and the specific heat of the specimen, were obtained from the A.S.T.M. manual (Ref. 4, p. 192).

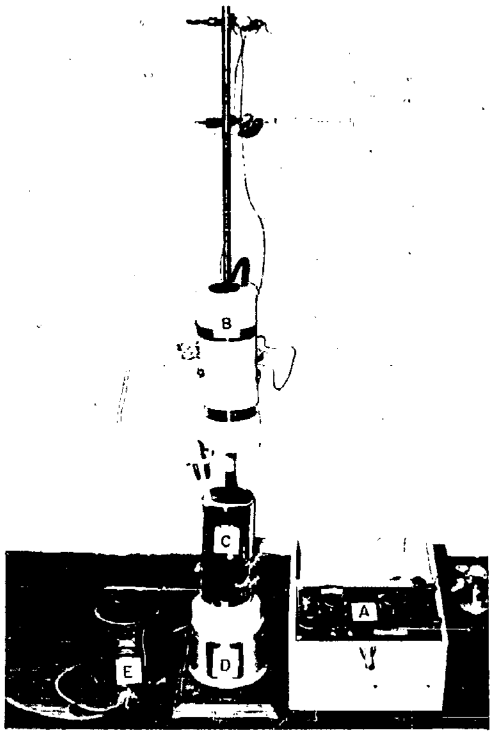

FIG. 5. Specific Heat Apparatus. (a) L & N potentiometer, (b) electric heater, (c) calorimeter, (d) magnetic stirrer, (e) Variac.

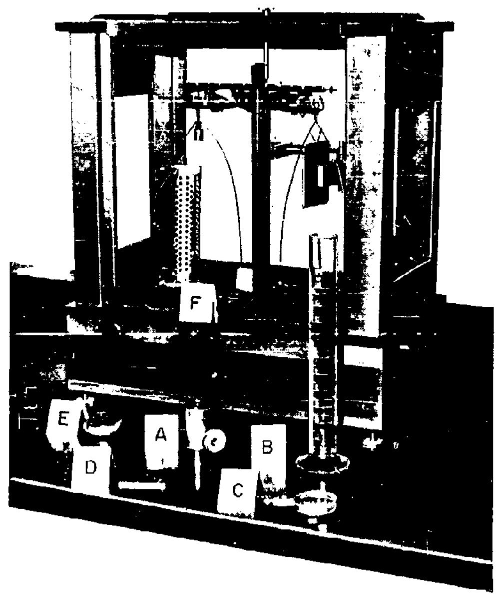

FIG. 6. Specific Heat Accessories. (a) Capsule assembly, (b) graduated cylinder, (c) magnifier, (d) standard copper bar, (e) stop watch, (f) balance.

To determine the water equivalent of the calorimeter, the same procedure was followed, except for the substitution of the copper bus bar standard for the capsule and specimen. The water equivalent of a body is defined as the mass of water that requires the same amount of heat as the body in order to change its temperature by an equal amount. The water equivalent, E, of the calorimeter is as follows:

$$E = \frac{M_r C_r (T_h - T_m)}{C_w (T_m - T_c)} - M_w$$

where T_h is the equilibrium temperature of the standard in the heater, T_c is the initial temperature of the calorimeter, and T_m is the extrapolated temperature of the mixture. The r and w refer to the standard and the distilled water, respectively. M is mass and C is heat capacity. The water equivalent of the calorimeter was found to be 32.37 grams.

The heat capacity of the capsule, C_c, with M_c as mass, was determined from the expression

$$C_c = \frac{(M_w + E) C_w (T_m - T_c)}{M_c (T_h - T_m)}$$

The specific heat of the capsule was 0.10 Btu/(lb)(°F). As in all determinations, at least three tests were performed and the average results reported.

Finally, the specific heat of the specimen was determined from the following expression:

$$C_s = \frac{\dfrac{(M_w + E)C_w(T_m - T_c)}{(T_h - T_m)} - M_c C_c}{M_s}$$

where C_s and M_s are, respectively, the specific heat and the mass of the test specimen.

DISCUSSION OF RESULTS

The thermal conductivities of the nine plastic laminates are shown in Tables 1 through 10, in Appendix A, and plotted as a function of temperature in Fig. 7 through 16. The specific heats of the plastic laminates are shown in Tables 11 through 18 in Appendix A. The thermal properties (thermal conductivity, specific heat, and thermal diffusivity) at 140°F and the density are shown in Table 19.

Thermal Conductivity. TIC-311S had the lowest thermal conductivity of the test materials. The thermal conductivity of 184 Volan impregnated with phenyl silane resin (samples 3 and 5) was the second lowest.

The temperature range for determining the thermal conductivity of TIC-311S was limited, since TIC intumesces when it is exposed to temperatures of 300°F or higher. At hot-plate temperatures of 230 and 300°F it released some foul-smelling liquid. This chemical reaction within the panel may account in part for the low values of thermal conductivity.

The thermal conductivity of graphite cloth impregnated with phenolic resin was higher than the thermal conductivities of the other plastic laminates, probably because of the presence of relatively large strands of graphite in the graphite cloth. The graphite cloth laminate had the only thermal conductivity that definitely decreased with an increase in temperature; this behavior is similar to that of pure graphite in this temperature range.

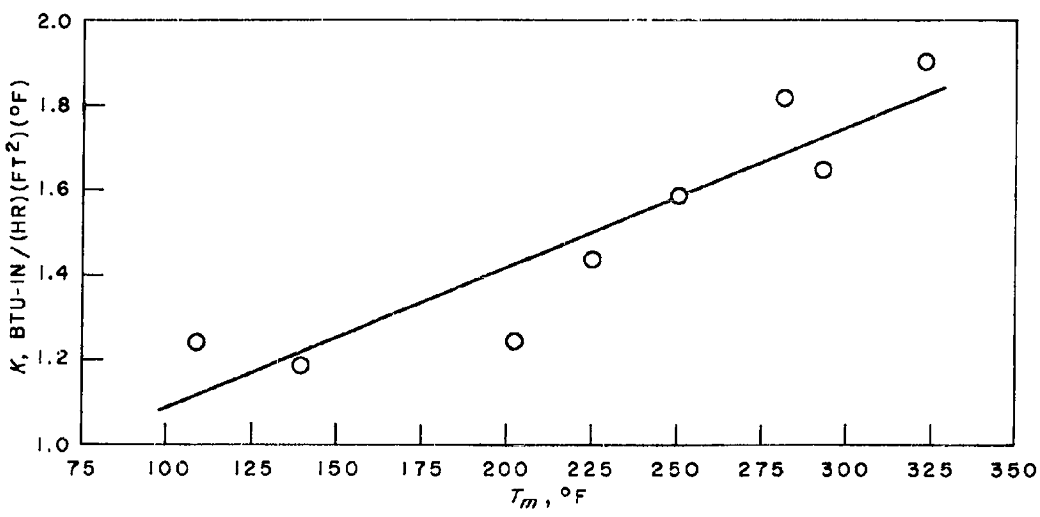

FIG. 7. Thermal Conductivity of Graphite Mat Impregnated With Phenolic Resin.

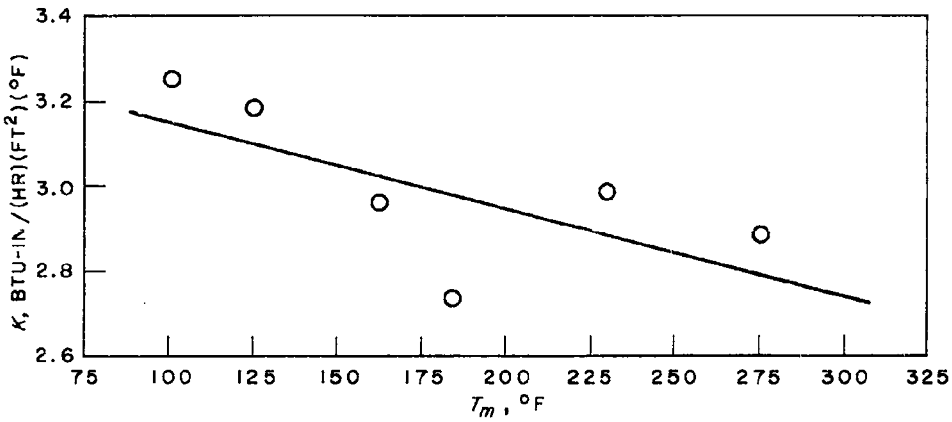

FIG. 8. Thermal Conductivity of Graphite Cloth Impregnated With Phenolic Resin.

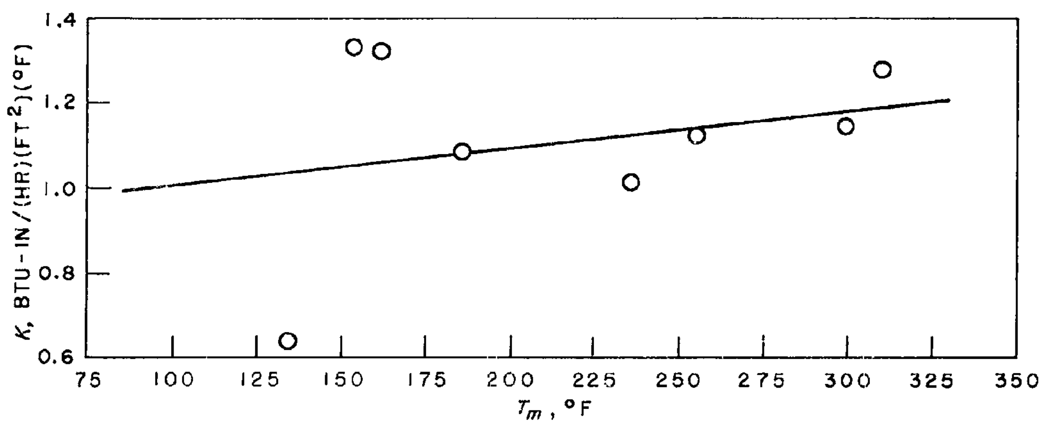

FIG. 9. Thermal Conductivity of 184 Volan Impregnated With Phenyl Silane Resin.

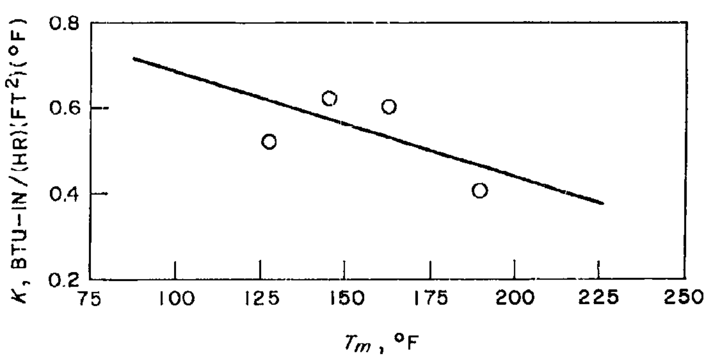

FIG. 10. Thermal Conductivity of TIC-311S.

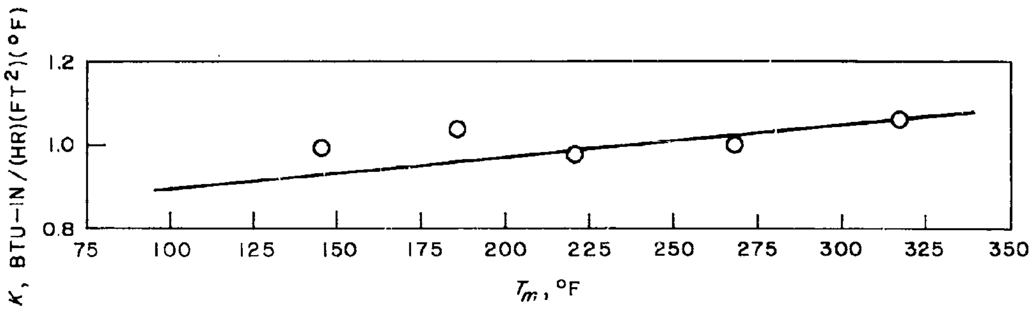

FIG. 11. Thermal Conductivity of 184 Volan Impregnated With Phenyl Silane.

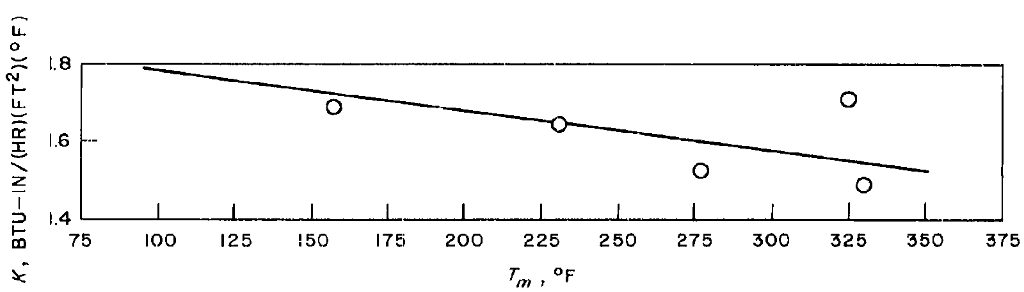

FIG. 12. Thermal Conductivity of Asbestos Cloth With Single Sheet of Silver Foil Impregnated With Phenolic Resin.

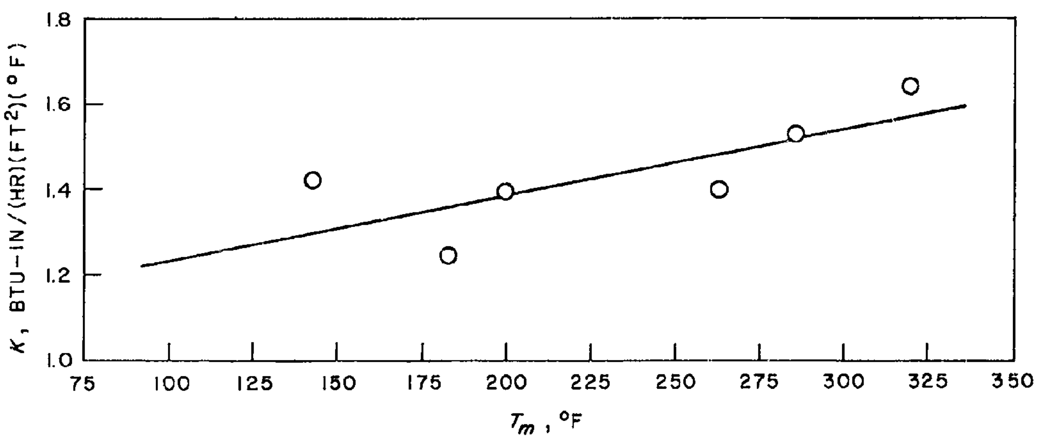

FIG. 13. Thermal Conductivity of Asbestos Cloth With Single Sheet of Aluminum Foil Impregnated With Phenolic Resin.

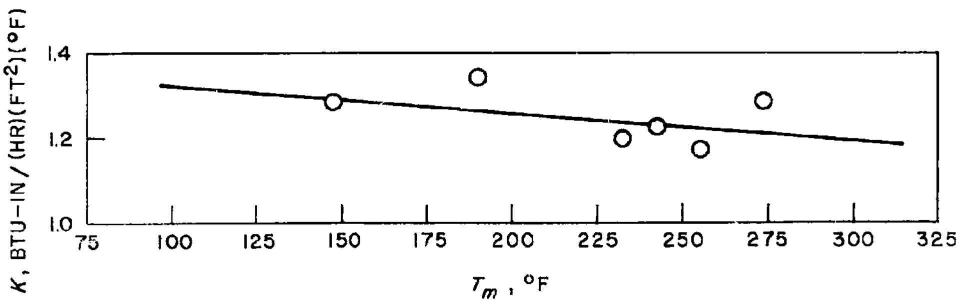

FIG. 14. Thermal Conductivity of Refrasil Cloth Impregnated With Phenolic Resin.

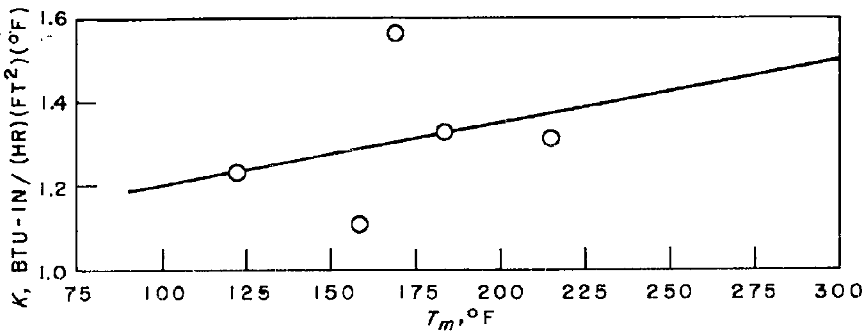

FIG. 15. Thermal Conductivity of 184 Volan Impregnated With Phenyl Silane Resin With 2-Mil Coat of SAF Paint.

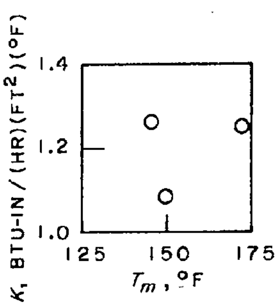

FIG. 16. Thermal Conductivity of 184 Volan Impregnated With Phenyl Silane Resin With 2-Mil Coat of TIC Paint.

The 184 Volan and Refrasil laminates were discolored when exposed to temperatures of about 475°F. The other laminates, with the exception of TIC-311S, had no visible signs of deterioration after the thermal conductivity determinations.

The thermal conductivity of asbestos cloth with a metal foil in the center and impregnated with phenolic resin was higher for all specimens, except the graphite laminates. It appears that an aluminum foil is more effective than a silver foil, which is what one would expect since aluminum has a lower thermal conductivity than silver. However, it is believed that the resin content and the method of adhering the metal foil to the asbestos cloth had a greater effect on the thermal conductivity than the choice of metal foil.

The thermal conductivities of the two painted test specimens (samples 9 and 10) were higher than the unpainted test specimens (samples 3 and 5). The temperature range available for determining thermal conductivity of the two painted test specimens was limited because of the constituents of SAF and TIC paints, which decompose at approximately 300°F.

Expressions relating the thermal conductivity of the first nine samples to temperature were obtained by the method of least squares (Appendix A) and should be accurate to two significant figures. Sample calculations using the method of least squares are given in Appendix B.

Specific Heat. The values of mean specific heat ranged from 0.35 Btu/(lb)(°F) for TIC-311S to 0.24 Btu/(lb)(°F) for Refrasil cloth impregnated with phenolic resin for the temperature range of 75 to 212°F. For purposes of comparison, the specific heats of the two painted test specimens were calculated.

Thermal Diffusivity. TIC-311S had the lowest thermal diffusivity (0.0021 ft^2/hr) at 140°F of the test materials because of its low thermal conductivity and high specific heat. The next lowest values of thermal diffusivity were recorded for the 184 Volan laminate (0.0028 ft^2/hr) and for the asbestos cloth with aluminum foil laminate (0.0031 ft^2/hr).

Graphite cloth impregnated with phenolic resin had the highest thermal diffusivity (0.0120 ft^2/hr) at 140°F of the test materials. The reason for this high value is the high thermal conductivity and low density of the graphite cloth laminate.

RECOMMENDATIONS

The following recommendations are made for the thermal conductivity apparatus: (1) addition of a temperature control to maintain constant temperature of the cooling water, (2) installation of the apparatus in an area where a relatively constant temperature is realized, and (3) addition of a power regulator to prevent power fluctuations.

The following recommendations are made for the specific heat apparatus: (1) installation of the apparatus in an area where the temperature is relatively constant at 68 to 72°F, (2) addition of a power regulator, because of the sensitivity of the capsule temperature with fluctuations in power, and (3) substitution of other liquids of known specific heat for distilled water to extend the test-temperature range.

The last recommendation is that a radiant heat facility be constructed for determining the thermal diffusivity of materials as well as other thermal properties, directly. This apparatus would complement the guarded hot plate and specific heat apparatus at elevated temperatures.

The radiant heat apparatus should consist of quartz tube lamps with tungsten filaments as the heat source, and thermocouples on the surface of the test specimen to monitor the surface temperature. The thermocouples on the surface would ensure that a constant heat flux is absorbed by the test specimen. From a plot of temperature versus time the thermal diffusivity of a material could be determined according to Eq. 5.

Appendix A
THERMAL PROPERTIES

TABLE 1. THERMAL CONDUCTIVITY OF GRAPHITE MAT IMPREGNATED WITH PHENOLIC RESIN

Run	$Q, \frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	132.0	1.00	130	86	108	1.24
2	192.0	0.98	173	105	139	1.19
3	2432.0	6.43	264	139	202	1.25
4	7065.0	9.30	334	116	225	1.44
5	4410.0	4.80	369	130	250	1.59
6	1125.0	1.08	399	163	281	1.82
7	6565.0	5.58	441	145	293	1.65
8	406.5	3.65	443	200	322	1.90

$L = 0.141$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of graphite mat impregnated with phenolic resin with temperature is $K = 0.752 + 0.00334T$ for the temperature range studied.

TABLE 2. THERMAL CONDUCTIVITY OF GRAPHITE CLOTH IMPREGNATED WITH PHENOLIC RESIN

Run	$Q, \frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	347.5	1.25	122	81	101	3.25
2	475.0	1.08	158	92	125	3.18
3	1320.0	2.00	215	108	162	2.96
4	924.0	1.00	265	103	184	2.73
5	1540.0	1.38	318	140	229	2.98
6	901.0	1.00	351	201	276	2.88

$L = 0.163$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of graphite cloth impregnated with phenolic resin with temperature is $K = 3.35 - 0.002T$ fo- the temperature range studied.

TABLE 3. THERMAL CONDUCTIVITY OF 184 VOLAN IMPREGNATED WITH PHENYL SILANE RESIN

Run	$Q, \frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	356.0	2.50	187	81	134	0.66
2	1032.0	3.00	217	89	153	1.33
3	599.5	1.50	236	86	161	1.32
4	833.0	2.00	280	91	186	1.09
5	828.0	1.50	370	99	235	1.01
6	1430.0	2.00	406	104	255	1.13
7	1346.0	1.50	494	102	298	1.14
8	2504.0	2.25	508	111	310	1.28

$L = 0.168$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of 184 Volan impregnated with phenyl silane resin with temperature is $K = 0.926 + 0.00088T$ for the temperature range studied.

TABLE 4. THERMAL CONDUCTIVITY OF TIC-311S

Run	$Q, \frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	206.0	1.00	182	74	128	0.53
2	275.8	1.00	207	86	146	0.63
3	600.0	2.00	230	94	162	0.61
4	328.0	1.00	300	78	189	0.41

$L = 0.094$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of TIC-311S with temperature is $K = 0.890 - 0.002227T$ for the temperature range studied.

TABLE 5. THERMAL CONDUCTIVITY OF 184 VOLAN IMPREGNATED WITH PHENYL SILANE RESIN

Run	$Q, \frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	240.0	1.00	213	78	145	0.89
2	1322.0	3.25	285	87	186	1.04
3	729.0	1.50	344	95	220	0.98
4	647.5	1.00	428	107	268	1.01
5	828.5	1.00	512	122	317	1.06

$L = 0.170$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of 184 Volan impregnated with phenyl silane resin with temperature is $K = 0.824 + 0.000744T$ for the temperature range studied.

TABLE 6. THERMAL CONDUCTIVITY OF ASBESTOS CLOTH WITH SINGLE SHEET OF SILVER FOIL IMPREGNATED WITH PHENOLIC RESIN

Run	$Q, \frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	261.0	1.00	215	100	157	1.69
2	851.0	1.50	369	93	231	1.65
3	1333.0	2.00	442	115	278	1.52
4	1223.0	1.75	495	154	325	1.71
5	783.5	1.00	525	134	329	1.49

$L = 0.254$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of asbestos cloth with a single sheet of silver foil impregnated with phenolic resin with temperature is $K = 1.90 - 0.0011T$ for the temperature range studied.

TABLE 7. THERMAL CONDUCTIVITY OF ASBESTOS CLOTH WITH SINGLE SHEET OF ALUMINUM FOIL IMPREGNATED WITH PHENOLIC RESIN

Run	$Q, \frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	539.5	2.43	192	92	142	1.42
2	500.0	2.00	246	117	182	1.24
3	450.0	1.00	302	95	198	1.39
4	527.0	1.00	383	143	263	1.41
5	1628.0	2.00	455	115	285	1.53
6	816.5	1.00	484	155	319	1.64

$L = 0.281$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of asbestos cloth with a single sheet of aluminum foil impregnated with phenolic resin with temperature is $K = 1.09 + 0.00149T$ for the temperature range studied.

TABLE 8. THERMAL CONDUCTIVITY OF REFRASIL CLOTH IMPREGNATED WITH PHENOLIC RESIN

Run	$Q, \frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	494.0	2.00	195	99	147	1.28
2	387.4	1.00	262	117	189	1.34
3	680.0	1.00	373	91	232	1.20
4	663.5	1.00	378	107	242	1.22
5	809.0	1.75	355	165	260	1.17
6	896.5	1.00	448	98	273	1.28

$L = 0.170$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of Refrasil cloth impregnated with phenolic resin with temperature is $K = 1.42 - 0.000706T$ for the temperature range studied.

TABLE 9. THERMAL CONDUCTIVITY OF 184 VOLAN IMPREGNATED WITH PHENYL SILANE RESIN WITH 2-MIL COAT OF SAF PAINT

Run	Q, $\frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	K, $\frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	224.0	1.17	161	83	122	1.23
2	666.0	2.00	233	83	158	1.11
3	520.0	1.00	251	85	168	1.57
4	877.5	1.00	237	127	182	1.33
5	292.0	1.00	269	159	214	1.32

$L = 0.170$ in. $A = 0.34$ ft^2

The relationship of thermal conductivity of 184 Volan impregnated with phenyl silane resin with a 2-mil coat of SAF paint with temperature is $K = 1.06 + 0.00149T$ for the temperature range studied.

TABLE 10. THERMAL CONDUCTIVITY OF 184 VOLAN IMPREGNATED WITH PHENYL SILANE RESIN WITH 2-MIL COAT OF TIC PAINT

Run	Q, $\frac{\text{Btu}}{\text{hr}}$	t, hr	T_1, °F	T_2, °F	$T_{1,2}$, °F	K, $\frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$
1	410.0	1.50	201	91	146	1.26
2	350.0	1.50	205	95	150	1.08
3	420.0	1.00	257	87	172	1.25

$L = 0.172$ in. $A = 0.34$ ft^2

Three determinations of thermal conductivity at different temperatures are not sufficient to establish the relationship of thermal conductivity of the test materials with temperature.

TABLE 11. SPECIFIC HEAT OF GRAPHITE MAT IMPREGNATED WITH PHENOLIC RESIN

Run	T_h, °F	T_m, °F	C_s, $\frac{\text{Btu}}{(\text{lb})(°\text{F})}$
1	217	75	0.29
2	214	73	0.28
3	217	75	0.27

The mean specific heat of graphite mat impregnated with phenolic resin over the temperature range 75 to 212°F may be taken as 0.28 Btu/(lb)(°F).

TABLE 12. SPECIFIC HEAT OF GRAPHITE CLOTH IMPREGNATED WITH PHENOLIC RESIN

Run	T_h, °F	T_m, °F	C_s, $\frac{\text{Btu}}{(\text{lb})(°\text{F})}$
1	211	81	0.25
2	207	81	0.31
3	203	80	0.26

The mean specific heat of graphite cloth impregnated with phenolic resin over the temperature range 75 to 212°F may be taken as 0.27 Btu/(lb)(°F).

TABLE 13. SPECIFIC HEAT OF 184 VOLAN IMPREGNATED WITH PHENYL SILANE RESIN

Run	T_h, °F	T_m, °F	C_s, $\frac{\text{Btu}}{(\text{lb})(°\text{F})}$
1	204	79	0.27
2	209	79	0.26
3	203	79	0.25

The mean specific heat of 184 Volan impregnated with phenyl silane resin over the temperature range 75 to 212°F may be taken as 0.26 Btu/(lb)(°F).

TABLE 14. SPECIFIC HEAT OF TIC-311S

Run	T_h, °F	T_m, °F	C_s, $\frac{\text{Btu}}{(\text{lb})(°\text{F})}$
1	210	82	0.35
2	212	82	0.35
3	203	82	0.36

The mean specific heat of TIC-311S over the temperature range 75 to 212°F may be taken as 0.35 Btu/(lb)(°F).

TABLE 15. SPECIFIC HEAT OF 184 VOLAN IMPREGNATED WITH PHENYL SILANE RESIN

Run	T_h, °F	T_m, °F	C_s, $\frac{\text{Btu}}{(\text{lb})(°\text{F})}$
1	203	80	0.23
2	205	70	0.23
3	202	79	0.24

The mean specific heat of 184 Volan impregnated with phenyl silane resin over the temperature range 75 to 212°F may be taken as 0.23 Btu/(lb)(°F).

TABLE 16. SPECIFIC HEAT OF ASBESTOS CLOTH WITH SINGLE SHEET OF SILVER FOIL IMPREGNATED WITH PHENOLIC RESIN

Run	T_h, °F	T_m, °F	C_s, $\frac{\text{Btu}}{(\text{lb})(°\text{F})}$
1	206	78	0.29
2	209	82	0.30
3	205	79	0.28

The mean specific heat of asbestos cloth having a single sheet of silver foil impregnated with phenolic resin over the temperature range 75 to 212°F may be taken as 0.29 Btu/(lb)(°F).

TABLE 17. SPECIFIC HEAT OF ASBESTOS CLOTH WITH SINGLE SHEET OF ALUMINUM FOIL IMPREGNATED WITH PHENOLIC RESIN

Run	T_h, °F	T_m, °F	C_s, $\frac{\text{Btu}}{(\text{lb})(°\text{F})}$
1	209	80	0.33
2	216	78	0.30
3	213	81	0.32

The mean specific heat of asbestos cloth having a single sheet of aluminum foil impregnated with phenolic resin over the temperature range 75 to 212°F may be taken as 0.32 Btu/(lb)(°F).

TABLE 18. SPECIFIC HEAT OF REFRASIL CLOTH IMPREGNATED WITH PHENOLIC RESIN

Run	T_h, °F	T_m, °F	C_s, $\frac{\text{Btu}}{(\text{lb})(°\text{F})}$
1	210	78	0.24
2	205	80	0.25
3	210	81	0.24

The mean specific heat of refrasil cloth impregnated with phenolic resin over the temperature range 75 to 212°F may be taken as 0.24 Btu/(lb)(°F).

TABLE 19. THERMAL PROPERTIES OF THE NINE PLASTIC LAMINATES AT 140°F

Material	$K, \frac{\text{Btu-in}}{(\text{hr})(\text{ft}^2)(°\text{F})}$	$C, \frac{\text{Btu}}{(\text{lb})(°\text{F})}$	$\rho, \frac{\text{lb}}{\text{ft}^3}$	$\alpha, \frac{\text{ft}^2}{\text{hr}}$
Graphite mat impregnated with phenolic resin	1.22	0.28	66.4	0.0055
Graphite cloth impregnated with phenolic resin	3.07	.27	79.6	.0120
184 Volan impregnated with phenyl silane resin	1.05	.26	121.0	.0028
TIC-311S	0.61	.35	67.6	.0021
184 Volan impregnated with phenyl silane resin	0.93	.23	120.5	.0028
Asbestos cloth with silver foil impregnated with phenolic resin	1.75	.29	113.0	.0045
Asbestos cloth with aluminum foil impregnated with phenolic resin	1.30	.32	107.8	.0031
Refrasil cloth impregnated with phenolic resin	1.31	.24	97.0	.0047
184 Volan impregnated with phenyl silane resin with SAF paint	1.27	.26[a]	120.2	.0034
Glass cloth impregnated with phenyl silane resin with TIC paint	1.14	0.23[a]	120.2	0.0034

[a] Calculated

Appendix B
SAMPLE CALCULATIONS

THERMAL CONDUCTIVITY

Data from Run 4 on 184 Volan impregnated with phenyl silane resin (sample 5):

$$Q = 647.5\ \text{Btu}/(\text{hr})(\text{ft}^2)$$
$$T_1 = 428°\text{F}$$
$$T_2 = 108°\text{F}$$
$$L = 0.170\ \text{in.}$$
$$A = 0.34\ \text{ft}^2$$
$$K = QL/A(T_1 - T_2)$$
$$K = (647.5)(0.170)/(0.34)(428 - 108)$$
$$K_{268°\text{F}} = 1.01\ \text{Btu-in}/(\text{hr})(\text{ft}^2)(°\text{F})$$

METHOD OF LEAST SQUARES (REF. 33, P. 369)

Establishing the linear relationship of K of 184 Volan impregnated with phenyl silane resin with temperature:

$$K = a + bT$$

where

$$a = \frac{N_a}{D},\ b = \frac{N_b}{D}$$

ΣT	ΣK	ΣT^2	ΣTK
145	0.889	21,025	128.905
186	1.04	34,596	193.440
220	0.975	48,400	214.500
268	1.01	71,824	270.680
317	1.06	100,489	336.020
1136	4.974	276,334	1143.545

$$n = 5$$

$$N_a = \begin{vmatrix} \Sigma K & \Sigma T \\ \Sigma TK & \Sigma T^2 \end{vmatrix} = \begin{vmatrix} 4.974 & 1136 \\ 1143.545 & 276{,}334 \end{vmatrix}$$

$$N_a = 75{,}418$$

$$N_b = \begin{vmatrix} n & \Sigma K \\ \Sigma T & \Sigma TK \end{vmatrix} = \begin{vmatrix} 5 & 4.974 \\ 1136 & 1143.545 \end{vmatrix}$$

$$N_b = 67.261$$

$$D = \begin{vmatrix} n & \Sigma T \\ \Sigma T & \Sigma T^2 \end{vmatrix} = \begin{vmatrix} 5 & 1136 \\ 1136 & 276{,}334 \end{vmatrix}$$

$$D = 91{,}174$$

therefore

$$a = N_a/D = 0.827$$

$$b = N_b/D = 0.000738$$

and

$$K = 0.827 + 0.000738T$$

SPECIFIC HEAT

Data from Run 1 on glass cloth impregnated with phenyl silane resin:

$$\begin{aligned} M_w &= 302.7 \text{ gr} & T_m &= 26.748°\text{C} \\ E &= 32.4 \text{ gr} & T_c &= 24.044°\text{C} \\ C_w &= 1.00 \text{ cal/(gr)(°C)} & T_h &= 95.2°\text{C} \\ M_c &= 34.60 \text{ gr} & M &= 42.43 \text{ gr} \\ C_c &= 0.10 \text{ cal/(gr)(°C)} \end{aligned}$$

$$C_s = \frac{\dfrac{(M_w + E)C_w(T_m - T_c)}{(T_h - T_m)} - M_c C_c}{M_s}$$

$$C_s = \frac{\dfrac{(302.7 + 32.4)(1.00)(26.748 - 24.044)}{(95.2 - 26.7)} - (34.60)(0.10)}{42.43}$$

$$C_s = 0.23 \text{ cal/(gr)(°C)}$$

or

$$C_s = 0.23 \text{ Btu/(lb)(°F)}$$

THERMAL DIFFUSIVITY

Data on glass cloth impregnated with phenyl silane resin at 140°F:

$$a = K/C\rho$$

$$a = \frac{0.929 \text{ Btu-in/(hr)(ft}^2\text{)(°F)}}{(0.23 \text{ Btu/(lb)(°F)})(120.5 \text{ lb/ft}^3)(12 \text{ in/ft})}$$

$$a = 0.0028 \text{ ft}^2\text{/hr}$$

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